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Target Physics

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4.3.1.1.ra Target Physics

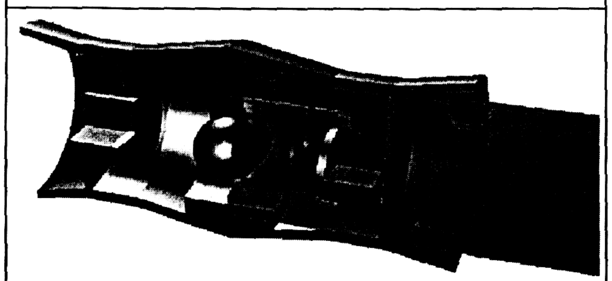
Inertial fusion targets can be categorized by the ignition scheme, the implosions mechanism and the driver technology used to supply the compression and the ignition energy. We will briefly review each of these elements. There are two ignition methods currently being considered. The first, called *hotspot ignition*, heats a central core of the compressed fuel to ignition temperatures. The assembly of a sufficiently large hotspot is accomplished by stagnation of a convergent flow. The assembled configuration of the hotspot, and surrounding compressed, low temperature fuel, will be approximately isobaric. The second ignition technique, called *fast ignition*, heats cold compressed fuel to ignition temperatures directly with an external source of heat. This technique has become practicable by the advent of short-pulse, high-intensity lasers using chirped-pulse-amplification (CPA), that can compress laser pulses to extremely high power. If focused appropriately, these fast-ignition laser beams can provide the same power densities as result from the hydrodynamic flow stagnation of the first technique.

Inertial fusion fuel can be compressed by two techniques, referred to as *direct* and *indirect* drive. Directly driven capsules directly absorb energy delivered by the external compression driver and use it to implode the fusion fuel. Indirectly driven targets absorb the external energy in material away from the capsule, which converts it into x-rays. The x rays are contained in a hohlraum fabricated from high atomic weight material, that symmetrizes the x rays. The capsule then absorbs these x-rays to compress the fuel

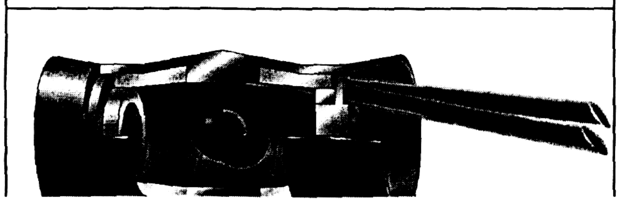
There are four compression drivers being developed for inertial fusion energy: *heavy ion accelerators* (with η = 25%-45% efficiency); *diode-pumped solid state lasers* (DPSSL) (with approximately 10% efficiency); *KrF lasers* (with approximately 7% efficiency), and *Z-pinches* (with 15-20% efficiency). Target designs differ in detail from driver to driver to accommodate the form of energy delivery while driving the capsules with adequate symmetry and producing adequate gain (*G*). The gain requirement is set so that less than about 25% (depending on the capital cost of the driver) of output electrical power is required to run the plant. This figure of merit corresponds to a driver-efficiency gain product (ηG) that is greater than 10.

In principle, we can choose a target concept by selecting one of sixteen combinations composed by matching an implosion technique, an ignition technique and a driver. The designs that have been studied most extensively use hotspot ignition. Most effort on target design has concentrated on the following three approaches: targets directly driven by lasers; targets indirectly driven by ion beams; and targets indirectly driven by Z-pinches. Figure 1 shows some of the possible configurations.

HI hybrid target



HI distributed radiator



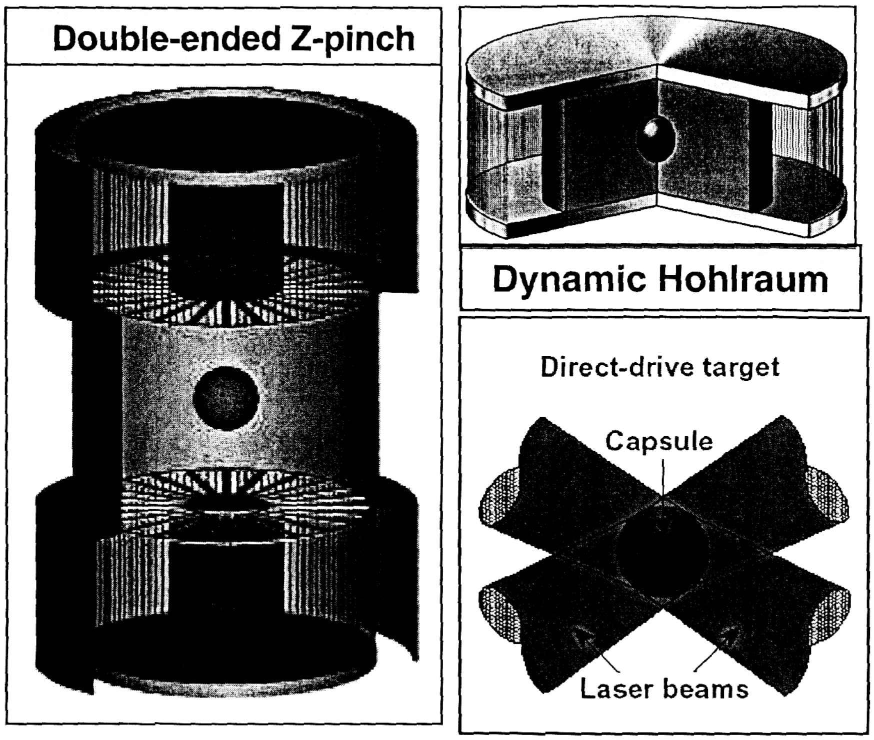


Figure 1. Shown are two Z-pinch designs (dynamic hohlraum and double ended), two heavy ion designs (distributed radiator and hybrid target) and a schematic of a direct drive laser design.

These hotspot ignited capsules designs are judged by three fundamental criteria: symmetry, stability and gain. The target designer must determine that the fuel will be imploded symmetrically; that it is sufficiently stable to prevent either shell break up in flight or excessive mixing of the hot ignition region with the cold main fuel; and that the design produces adequate gain. These target requirements set performance criteria for the rest of the system: driver scale and pulse shape to control fuel entropy in order to meet the gain requirement; illumination geometry to meet symmetry requirements; beam quality and smoothness to minimize seeds for hydrodynamic and plasma instabilities; beam brightness to control convergence ratio; ablator/fuel roughness to control final perturbation levels after amplification by the Rayleigh-Taylor instability; and hohlraum design and materials for symmetry control and coupling efficiency.

We can understand how the various requirements arise by beginning with ignition and working back to the implosion criteria. The stagnated fuel assembly is approximately isobaric. The energy invested in this assembly is the sum of the energy in the main fuel, given by a multiple of the Fermi-degenerate energy, and the hotspot. Minimizing this energy with respect to the pressure of the assembly leads to a minimum ignition energy . Detailed simulations of a wide range of implosions have found a scaling law: $E_{ign} \propto \alpha^{2.7} v_{impl}^{-7.2}$ where α is the ratio of the main fuel pressure to the Fermi-degenerate pressure at the fuel density and v_{impl} is the implosion velocity Hence, for a given energy invested in the fuel, higher implosion velocities have more "excess" energy above the minimum. This is interpreted as more 1-D (without transverse spatial perturbations) robustness.

How do the non-ideal effects manifest themselves as v_{impl} increases? Typically, peak drive pressure is limited by beam focusing capabilities or plasma instabilities. The acceleration distance is approximately half the original radius, R_I. Driving to higher velocities therefore requires larger initial radii and longer acceleration durations. As a rough estimate, we require that the compressed fuel have distortions less than half the compressed radius. This leads to a symmetry requirement that $\delta I/I < 1/2\ R_F/R_I$, where R_F is the converged radius and I is the incident intensity. Therefore, lower I and larger v_{impl} lead to more stringent symmetry requirements. These are met for direct drive systems by supplying enough beams (typically 60-90) arranged symmetrically. For indirect drive systems, the hohlraum and beam geometry are used to provide a symmetric flux on the implosion capsule. Three mechanisms symmetrize the drive. First, X rays are absorbed and re-emitted from the hohlraum walls multiple times, leading to a large number of effective scatters (which reduces the asymmetry). Second, the capsule samples much of the wall, wall-to-capsule transport smoothes spatial asymmetries with Legendre mode, l >5 by at least two orders of magnitude. Third, proper placement of beam spots can eliminate the low l modes. This simple analysis has been validated by 3D viewfactor calculations, integrated 2D/3D radiation transport/hydrodynamic calculations and in an extensive series of laser-driven experiments on the Nova and OMEGA lasers. Symmetry control at R_F/R_I exceeding IFE requirements will be demonstrated on the National Ignition Facility (NIF). This symmetry methodology generalizes from indirectly driven laser targets (where most of the database exists) to all of the indirectly driven concepts as recently confirmed by experiments on the Z facility at Sandia.

The growth rate of the Rayleigh-Taylor instability during the ablatively driven acceleration phase is of the form:

$$\gamma = a(Agk)^{1/2} - bkv_A ,$$

where a and b are of order 1, A is the Atwood number, k is the wave number and v_A is the ablation velocity, given by the mass ablation rate divided by the peak density. There are two ways to reduce the number of e-folds: shorten the implosion time (and reduce the implosion velocity) or change v_A by changing the adiabat of the implosion (and consequently the density). The first of these techniques improves capsule stability while reducing 1-D robustness and increasing gain. An optimization over implosion velocity for fixed drive pressure and coupled energy has been performed using multimode 2D direct numerical simulations with imposed perturbations on the outer ablator surface and the inner ice surface. Power-plant scale indirectly driven capsules with plastic ablators, when driven with a radiation temperature of 265 eV, gave full yield with 10-20 times the NIF roughness specification. This optimization can be tested at the NIF scale. Similar calculations have been performed for capsules tested at the Omega laser. The calculations and experiments agreed within a factor of 2.

Increasing the implosion adiabat (α) stabilizes the implosion. However, it reduces the 1-D robustness and the gain. Two dimensional multimode calculation of the directly driven α=3 NIF point design produces a gain of 30 at 1.5 MJ incident energy. This gain is insufficient for energy applications. However, by shaping the adiabat profile the fuel can be well compressed (on a low adiabat) to produce good gain, while the ablator can be placed on a high adiabat for adequate stability. This can be accomplished by sending an early time pressure spike through the shell. The decaying shock, thus produced maintains a low α for the fuel while raising it for the ablator. Recent single mode calculations suggest that this approach can produce gains above 100 for lasers of 2-4 MJ,,while maintaining adequate stability. Multimode calculations and Omega experiments are planned to verify this effect. The technique can also be tested on the NIF.

Fluctuations in the incident laser beam can imprint perturbations on direct-drive capsules. These perturbations act as seeds for subsequent Rayleigh-Taylor growth. Recent experiments on the Nike laser at NRL have shown that this imprint can be significantly reduced by overcoating the capsule with several tens of nanometers of high-Z metal.

The coupling of the beam to the plasma is an efficiency issue as well as affecting symmetry and implosion adiabat (through preheat). These issues have been studied extensively for laser-plasma coupling as part of the NNSA ignition program. Favorable coupling is essential for success of the ignition mission on NIF. For indirect drive, the major concerns are stimulated Brillioun scattering (inefficiency because light is scattered out of the hohlraum), stimulated Raman scattering (inefficiency andpreheat from high energy electrons generated in the coupling process) and filamentation (local hotspots driving other instabilities and beam deflections affecting symmetry). Currently, beam smoothing via SSD, and polarization smoothing, together with control of damping mechanisms by varying hohlraum gas compositions, seemto provide adequate control of these instabilities with blue light. In fact, recent experiments with green light have shown instability levels at the few percent level. The 2 plasmon decay instability is the principle concern for directly driven targets where this instability acts as a preheat source. Simple scaling of current experiments indicates that this source of preheat may be problematic at a power-plant scale. A remedy may be a reduction in peak laser intensity. In addition there is some evidence that the instability saturates at a tolerable level.

Heavy ion deposition is thought to be classical. However, there are theoretical uncertainties in particle ranges in dense plasmas. These are due mainly to uncertainties in the effective charge of the projectile. Experiments under relevant conditions (material density in the range 0.01-1.0 g/cc and temperature 100-300 eV) are just beginning or in the planning stages. Target designs canbe adjusted to accommodate factors of 2-3 uncertainties in particle ranges and deposition profiles varying from no-Bragg peak to a very sharp one. Possible sources of preheat come from gamma rays and projectile fragments produced in nuclear interactions as well as x rays produced during the ionization–recombination cycle of the projectile passing through the background plasma. Early estimates suggest that these preheating effects are tolerable. New calculations using current beam and target parameters should be performed.

Fast Ignition is a relatively new approach in which an external heating source drives the fusion hotspot to ignition temperatures. Its optimal target configuration for given absorbed energy corresponds to lower peak density than does the conventional implosion hotspot design. Hence, Fast Ignited targets converge less than do the conventional designs, leading to relaxed symmetry requirements and fabrication requirements. Finally, Fast Ignition leads to gain curves 2-3 times above conventional designs, leading to adequate gain for smaller drivers. Success of this approach requires three ingredients: assembly of an optimal fuel configuration; efficient coupling from the external heating source (nominally a short pulse laser although accelerator produced ion beams have also been suggested) to the plasma to generate relativistic electrons; and the coupling of the relativistic electrons to the ignition region (either directly or via ion intermediates).

Experiments over the past decade have shown coupling efficiencies from laser light to relativistic electrons in the range 15-50% with the coupling efficiency positively correlated with laser intensity. Proton beams have been formed with efficiency 1-25%. The leading design to assemble the compressed fuel is the cone focus target in which a dense annular cone is inserted into the side of a capsule. The fuel is compressed along the outside of the cone, and the interior of the cone gives the ignition laser beam access to the imploded core. Recent experiments at GEKKO XIII at ILE, Osaka using this design showed a hundred-fold increase in neutron yield when the short-pulse ignitor beam was timed with peak compression. The inferred energy coupling of the ignitor laser to the compressed fuel was 20-30%. A detailed understanding of electron transport is required to see if these results scale to power-plant conditions. Optimized implosion designs are also necessary. Recent proposals for NNSA-funded multi-kJ class short pulse lasers co-located with compression drivers may lead to an ignition/high gain demonstration using Fast Ignition.

The following summarizes the outstanding target physics issues for the various concepts.

Direct drive laser:

Symmetry: Adequate with quasi-uniform illumination with 60-90 appropriately shaped beams. No designs are available for asymmetric illumination if required by chamber considerations.

Stability: Picket fence pulse-shape designs have much better stability properties than previous designs and lead to adequate gain in the 2-3 MJ laser drive regime. Experiments and design improvements are still possible. Multi-mode calculations are required.

Coupling: Two plasmon decay instability may lead to unacceptable preheat. This would limit peak laser intensity.

Indirect drive ion beam:

Gain: Calculations show adequate gain for several illumination assumptions.

Stability: Capsules with plastic ablators are predicted to be adequately stable in multimode stability calculations.

Coupling: More data is necessary concerning the stopping power of ion beams in denseplasmas . In addition theoretical predictions that there are no significant collective beam plasma effects need to be verified experimentally.. On the other hand, the target designs can be tuned to accommodate large uncertainties. Some design features need experimental verification beyond current data: pressure balanced hohlraums and capsule shims.

Indirect drive Z-pinch:

Gain: Two designs produce adequate gain at large (but for Z-pinch acceptable) drive energies. Need to demonstrate pulse shaping with adequate reproducibility.

Symmetry: Experiments of two-sided hohlraum demonstrated Legendre mode=2 control at convergence ratio 10. Reactor capsules have convergence ratios in excess og 30 . Dynamic hohlraum showed hohlraum shell not too broken up at CR 8.

Indirect drive laser:

Gain: Need design with adequate gain. Best current design has gain=45 and 2.4 MJ of blue light.

Coupling: SBS, SRS, filamentation appear to be adequately controlled with beam smoothing control, but continuing work is necessary.

Symmetry: A two-sided design is needed if there is to be geometry advantage relative to direct drive.

Direct drive with ion beams:

Gain: Offers improved gain compared to other ion beam options.

Stability: Early calculations showed poor stability properties. Recent calculations suggest that the earlier work was pessimistic.

Symmetry: No existing direct drive ion beam designs are consistent with two-sided illumination.

Coupling: This approach is more sensitive to details of beam-plasma interaction than indirect drive ion beams.

Fast ignition:

Gain: Offers marked improvement of gain curve and relaxed stability and symmetry requirements for any driver. Techniques are needed that efficiently convert kinetic energy to compressional energy without forming a low-density central region.

Stability and Symmetry: Need to quantify how much stability and symmetry are relaxed.

Coupling: Cone focus design significantly reduces distance between critical surface and ignition region. Electron transport requires detailed modeling and continuing experimental program.

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